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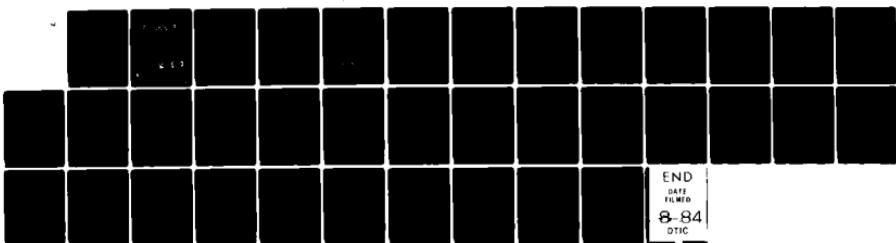
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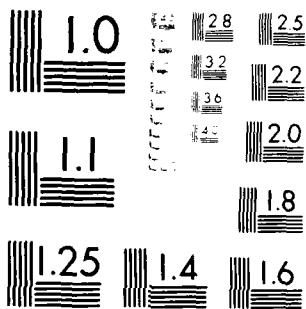
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Modifications to Iterative Recursion Unfolding Algorithms and Computer Codes to Find More Appropriate Neutron Spectra

K. A. LOWRY AND T. L. JOHNSON

Health Physics Staff

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Modifications were made to iterative recursion unfolding algorithms and computer codes which allow the incorporation of prior knowledge, such as cutoff energy or preferred spectral shape, into the solution. Using these modifications, more appropriate neutron spectra are obtained.

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MODIFICATIONS TO ITERATIVE RECURSION UNFOLDING ALGORITHMS AND COMPUTER CODES TO FIND MORE APPROPRIATE NEUTRON SPECTRA

INTRODUCTION

The unfolding of neutron spectra using data from activation foils, Bonner spheres, or other detectors usually involves solving an equation of the form

$$Y_j = \int_{E_{min}}^{E_{max}} A_j(E) \, X(E) \, dE \qquad\qquad (1)$$
$$j = 1,2,3\cdots M$$

where $X(E)$ represents the fluence distribution of the energy of the neutrons, Y_j is the response of the jth detector, $A_j(E)$ describes the response of the jth detector to neutrons of energy E, and M is the total number of detectors. Equation (1) is a degenerate case of a Fredholm integral equation of the first kind.

Although several methods exist for the formal solution of first-order integral equations, none of these methods are generally applicable when the detector response function $A_j(E)$ is not known analytically. This is the case for all practical systems used for neutron spectrometry. In practice, $A_j(E)$ is experimentally determined and/or calculated and is usually approximated by a response matrix having discrete values. Equation (1) is then replaced by a set of linear equations, and one is left with the problem of solving M equations in N unknowns, where M is the number of detectors available and N is the number of points needed to define the neutron spectrum. In matrix notation we have

$$\overline{Y} = A\overline{X} \, . \qquad\qquad (2)$$

Usually N is greater than M, hence no unique solution exists, and even when $N \leq M$ the response matrix A is usually ill-conditioned resulting in wildly oscillating, sometimes negative, solutions having little physical significance. This led Gold [1] to introduce the terms "exact,", "approximate", and

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"appropriate" to characterize the solutions to equation (2). An exact solution, if one exists, satisfies the equation exactly but may be negative or oscillatory. Approximate solutions satisfy the equation only within reasonable error limits. From the approximate solutions, selection of the most physically acceptable solution yields an appropriate solution, which usually is not unique.

Methods for solving equations (1) and (2) for neutron spectrometry have been summarized by Nachtigall and Burger [2] and by Patterson and Thomas [3]. One method which finds a non-negative solution to equation (2) by minimizing through an iterative recursion procedure the deviation between the measured and calculated detector responses has been described by Scofield [4] and Gold [1]. This method was modified by O'Brien et al [5] and Sanna [6], who called the computer code used to unfold the spectrum BON31G. More recently, Dorashenkc et al [7] have described another iterative recursion method for spectrum unfolding. A computer code SPUNIT, which uses this algorithm, has been written at Pacific Northwest Labs by Brackenbush and Scherpelz [8]. In addition to non-negativity of the solution, advantages usually listed for such iterative recursion methods of spectrum unfolding are ease of programming, and the possibility of adding smoothing to the solution. However, the application of other prior knowledge, such as cutoff energy or preferred spectral shape, has not been incorporated into the solution. It is our purpose to show how this may be accomplished in order to find more appropriate neutron spectra with these solution methods.

EFFECT OF INITIAL SOLUTION AND SMOOTHING METHOD

In Fig. 1 we show a typical neutron spectrum that has been unfolded from Bonner sphere data using BON31G or SPUNIT and the Sanna response matrix [9]. This spectrum was produced by moderating a Cf-252 fission source by placing it at the center of a 60 cm dia. steel sphere. The spectrum was further moderated by interposing a 60 cm x 60 cm x 3.8 cm thick Lucite slab between the steel ball and the Bonner sphere detectors. Detector counts were greater than 10K giving counting errors of approximately 1%. The spectrum shown in Fig. 1 is typical of spectra unfolded from Bonner sphere data in that there are few neutrons in the intermediate energy region (10^{-6} - 10^{-2} MeV) giving rise to the so-called "Bonner dip". Also, the high energy end of the spectrum

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does not decrease as rapidly as calculations suggest [10]. Similarly shaped spectra are often also obtained with other unfolding codes such as LOUHI [11] which can incorporate prior knowledge into the solution [12, 13]. We shall see that the physically unreasonable spectrum shape shown in Fig. 1 is caused by the starting solution and the smoothing algorithm used.

It is usually stated that the shape of the initial solution has little or no influence on the final solution for recursion methods [6, 7]. That this is not the case is illustrated in Fig. 2. Using SPUNIT and the same data as in Fig. 1, spectra were unfolded using two drastically different initial solutions. One initial solution was a 1/E spectrum, i.e., a straight horizontal line on the lethargy scale shown. The second had alternate initial spectral values differing by a factor of 10. No smoothing was used in either case. Note that after 1000 iterations the spectrum unfolded with alternate factor of 10 initial values still retains this characteristic. Even after 5000 iterations this characteristic remained. Both spectra shown in Fig. 2 fit the experimental data with an average error less than 1%. The fact that both spectra fit the data so well indicates that Bonner sphere data cannot produce spectra having great resolution, hence their dependence on the initial solution. Using BON31G, we obtained similar results, however, 3000 iterations were necessary to fit the experimental data within 1%.

The smoothing algorithm also affects the shape of the spectrum shown in Fig. 1. The smoothing used was as follows:

$$X_s(i) = (SX(i-1) + X(i) + SX(i+1))/1+2S), \qquad i = 2,3\cdots N-1 \qquad (3)$$

$$X_s(1) = X(1), \qquad (3a)$$

$$X_s(N) = X(N), \qquad (3b)$$

where X is the value of spectrum before smoothing, X_s is the value of the spectrum after smoothing, and S is the smoothing factor. Smoothing was done on each iteration with S = 0.01. Sanna [6] used an equivalent equation with S = 0.05, smoothing on alternate iterations. X(1) and X(N) were also smoothed.

An examination of equation (3) reveals that this smoothing also tends to bias the solution to a 1/E spectrum. To eliminate this bias, Sanna later

removed smoothing completely [14, 15]. Hence, his earlier finding [6] that the final solution was independent of starting solution was probably caused by the introduction of smoothing. Using smoothing, we also obtained the same final solution for all starting spectra.

BIASING THE SOLUTION TO OTHER STARTING SPECTRA

The previous results indicate that the starting solution does affect the final solution, hence, it would seem appropriate to choose the most physically reasonable spectrum for a starting solution. Most neutron spectra encountered in radiation protection work are produced by the scattering, moderation, and absorption of neutrons originally produced by nuclear fission, particle accelerators, or by the α,n reaction from radioactive sources. These processes tend to produce spectra that can be characterized as having a high energy peak corresponding, or reduced somewhat by moderation, to the original neutron source energy, a $(1/E)^x$ intermediate energy component produced by elastic scattering, and a thermal peak whose magnitude is determined by the atomic number of the shielding and scattering material and by the thermal neutron absorption cross-section of these materials. We therefore developed an algorithm called MAXIET [16] for use in YOGI [17] to find the best solution made up of these three spectrum components. This spectrum can then be used as an initial solution. Using the same data as Fig. 1 and 2, the spectra obtained using only MAXIET, and using MAXIET for an initial solution for SPUNIT, are shown in Fig. 3. Using only MAXIET, the average error on the detector responses is 1.1%; using MAXIET plus SPUNIT this error is reduced to 0.5%. No smoothing was used in either case. Note that using MAXIET and SPUNIT gives a spectrum that fits the data better, and agrees better with calculated spectra [10], than is obtained using a 1/E initial solution.

SMOOTHING TO OTHER STARTING SPECTRA

As previously noted, equation (3) biases the solution to a straight line, i.e., 1/E spectrum. What is needed is some method to bias the solution toward any chosen spectrum, e.g., the MAXIET initial spectrum. Perhaps the easiest way to do this is to make a transformation on the response matrix and the

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initial spectrum so that the transformed initial spectrum _is_ a straight line, i.e.,

$$A^T(i,j) = A(i,j) \, X_I(i) \qquad i = 1,2\cdots N \qquad (4)$$
$$j = 1,2\cdots M$$

$$X_I^T(i) = 1 \qquad i = 1,2\cdots N \qquad (5)$$

where A is the response matrix, A^T is the transformed response matrix, X_I is the initial spectrum, and X_I^T is the transformed initial spectrum.

The solution can then proceed using X_I^T and A^T to find the transformed solution X^T, using appropriate smoothing, e.g., equation (3). However, since the thermal neutron cross-sections of the shielding materials can tend to cause a very large or very small thermal neutron component, we do not smooth either the first or second energy intervals, i.e., equation (3) is replaced by

$$X_s^T(i) = (SX^T(i-1) + X^T(i) + SX^T(i+1))/(1+2S), \qquad (6)$$
$$i = 3,4\cdots N-1$$

$$X_s^T(1) = X^T(1) \qquad (6a)$$

$$X_s^T(2) = X^T(2) \qquad (6b)$$

$$X_s^T(N) = X^T(N) \qquad (6c)$$

Alternatively, if one wishes to tie the Nth spectral value to a fixed (N+1)th value, this is easily accomplished by letting the index in equation (6) go to N and eliminating equation (6c).

After solving for X^T, the final solution is obtained by making the inverse transformation, i.e.,

$$X(i) = X_I(i)X^T(i), \qquad i = 1,2\cdots N, \qquad (7)$$

To illustrate the use of smoothing to different starting spectra, errors of approximately 5% S.D. were introduced, using the algorithm in [6], to the

data used in the previous figures to simulate larger experimental errors. Spectra were then unfolded using a 1/E and a MAXIET starting spectrum using no smoothing, or equation (6) for smoothing with S = 0.05. These results are shown in Figs. 4 and 5. Note that using the MAXIET starting spectrum with smoothing to that spectrum gives more physically reasonable results than does the 1/E starting spectrum. More importantly, it can be seen that making the matrix transformation allows smoothing to any chosen initial spectrum.

PROGRAM BUNKI

The modifications which we have described to find more appropriate neutron spectra using BON31G or SPUNIT are incoporated in a computer program called BUNKI which is listed in Appendix A. BUNKI is written in FORTRAN IV and was coded for use on a DEC-10 computer. Tapes of the program and the response matrix file GIANT can be generated which are compatible with most mini or mainframe computers. Contact the authors for details.

The meanings cf most of the variables used in BUNKI are apparent from their use in the program. The definitions of the parameters which affect the spectrum and which may be input by the user are listed in Appendix B. Those which are not usually changed are written directly into the program, but they could also be input by the user, for example, at lines 27400-28000. Numbers in parentheses refer to relevant line number(s) for the parameters.

BUNKI is written to be run interactively from a terminal. Appendix C is an example of a BUNKI session in which two spectra are generated using the same Bonner sphere input data. In the first case, the user inputs the initial spectrum; in the second, the MAXIET algorithm is used to find the initial spectrum. The unformatted variables written back to the terminal as a guide for the user are listed at lines 39200 and 59400 of BUNKI. The questions which BUNKI asks the user indicate the many options available such as: choice of detectors, choice of unfolding code, choice of response matrix, choice of initial spectrum, and choice of the number of energy intervals, in addition to the input parameters in Appendix B.

The results of the spectrum unfolding are written directly to disc in a file called FOR01.DAT which is automatically generated by the DEC-10. In

addition, the lethargy spectrum data may be written to a file called SPECX.DAT which is used in a separate program to create plots of the spectra. The output of the session listed in Appendix C is listed in Appendix D.

CONCLUSION

By properly choosing the initial solution, and by smoothing to that solution by means of a transformation on the detector response matrix, it is possible to incorporate prior knowledge into the neutron spectra obtained using iterative recursion unfolding algorithms. We have written a computer code called BUNKI which incorporates these modifications into BON31G and SPUNIT. These modifications should also be useful for use in other unfolding algorithms and computer codes.

ACKNOWLEDGMENTS

We thank Larry Brackenbush and Bob Scherpelz of Pacific Northwe Labs for bringing to our attention SPUNIT and the work of Doroshenko et al / We are especially indebted to Bob Schwartz of the National Bureau of Standards whose question, "What causes that 'dip' in Bonner sphere spectra?", inspired us to do this work.
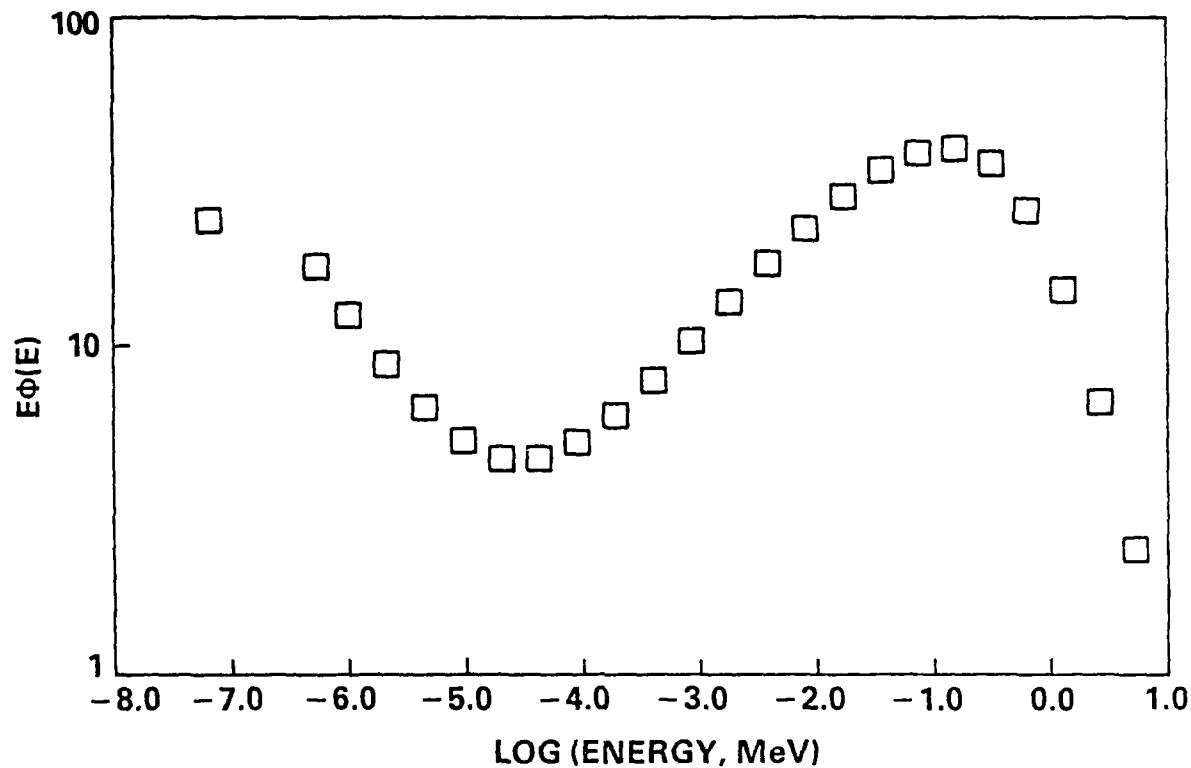
Fig. 1. Neutron spectrum of Cf-252 moderated by 30 cm of steel and 3.81 cm of Lucite. The spectrum was unfolded using SPUNIT (1000 iterations) from a 1/E starting spectrum and smoothed to that starting spectrum.
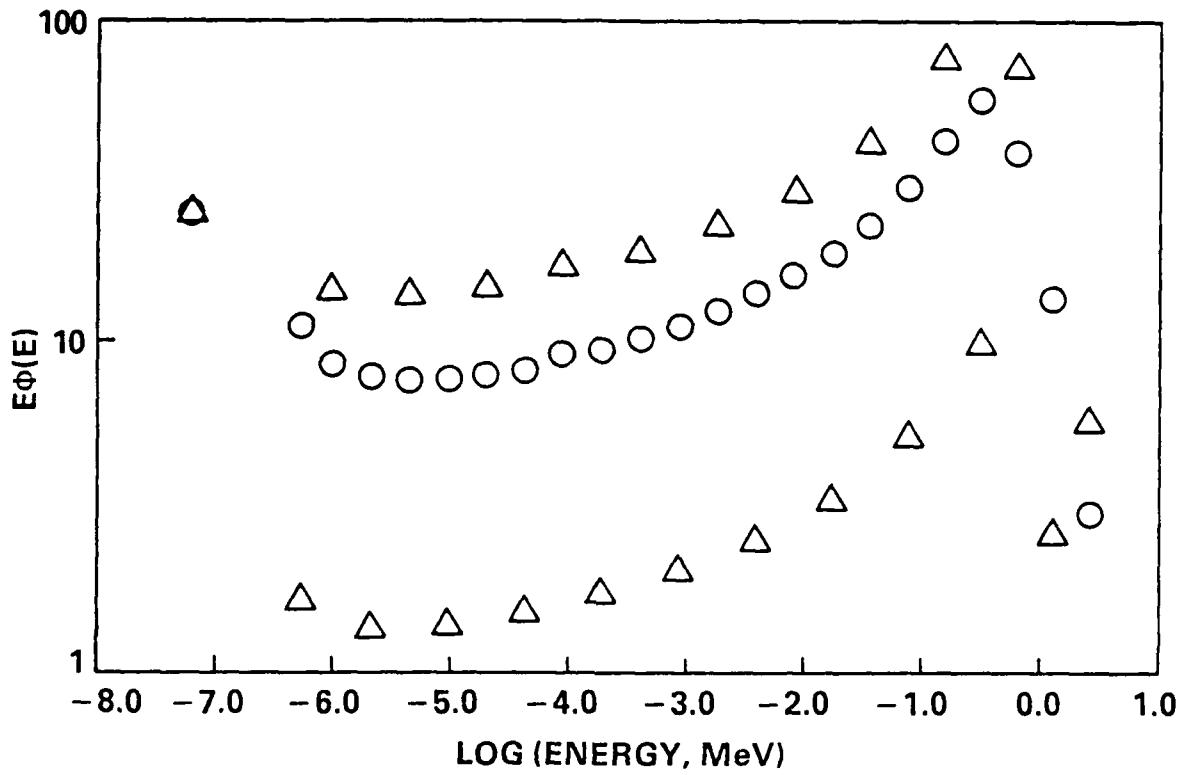
Fig. 2. Neutron spectra of Cf-252 moderated by 30 cm of steel and 3.81 cm of Lucite. The spectra were unfolded using SPUNIT (1000 iterations) using a 1/E starting spectrum (0), or using a starting spectrum with alternate initial values differing by a factor of 10 (Δ). No smoothing was used in either case.
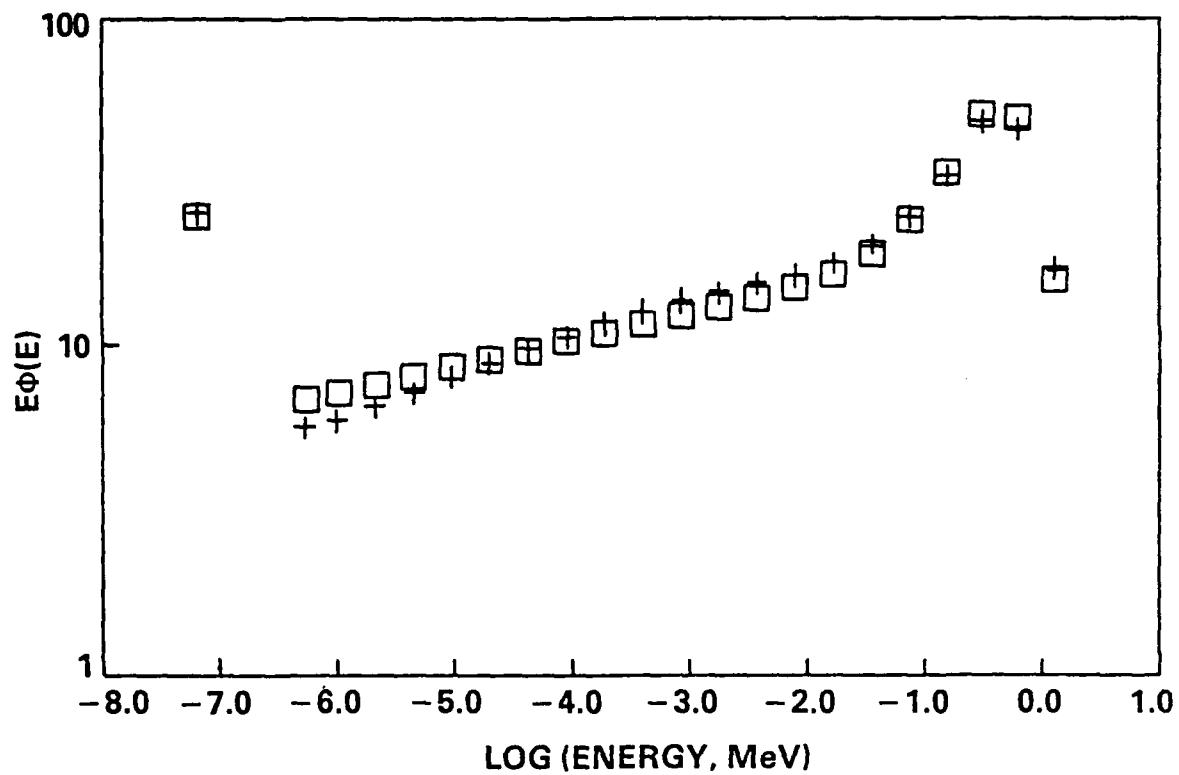
Fig. 3. Neutron spectra of Cf-252 moderated by 30 cm of steel and 3.81 cm
of Lucite. The spectra were unfolded using the MAXIET algorithm
(□), and using the MAXIET spectrum as an initial solution for
SPUNIT (1000 iterations) (+). No smoothing was used in either
case.

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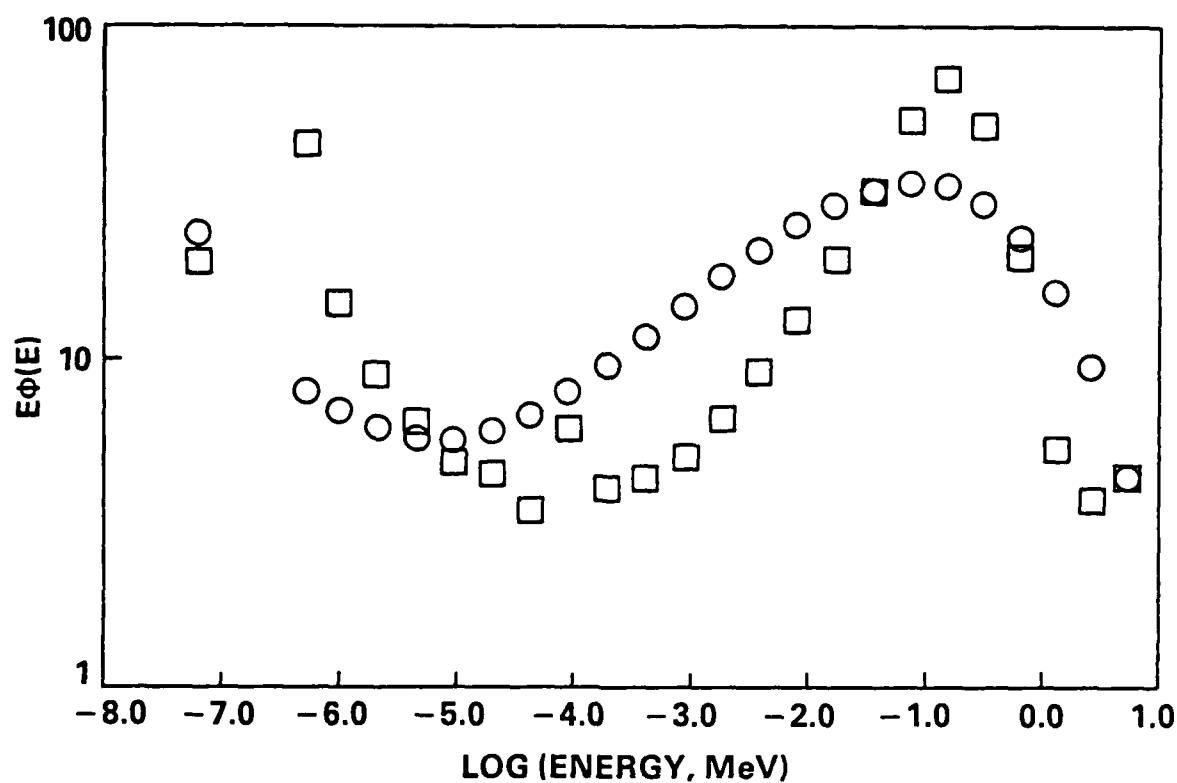
Fig. 4. Spectra unfolded using the same data as the previous figures with additional errors of 5% introduced to simulate larger experimental errors. Spectra were unfolded using SPUNIT (1000 iterations) from a 1/E starting spectrum with no smoothing (□), or with smoothing to the starting spectrum (0), using the method described in the text.
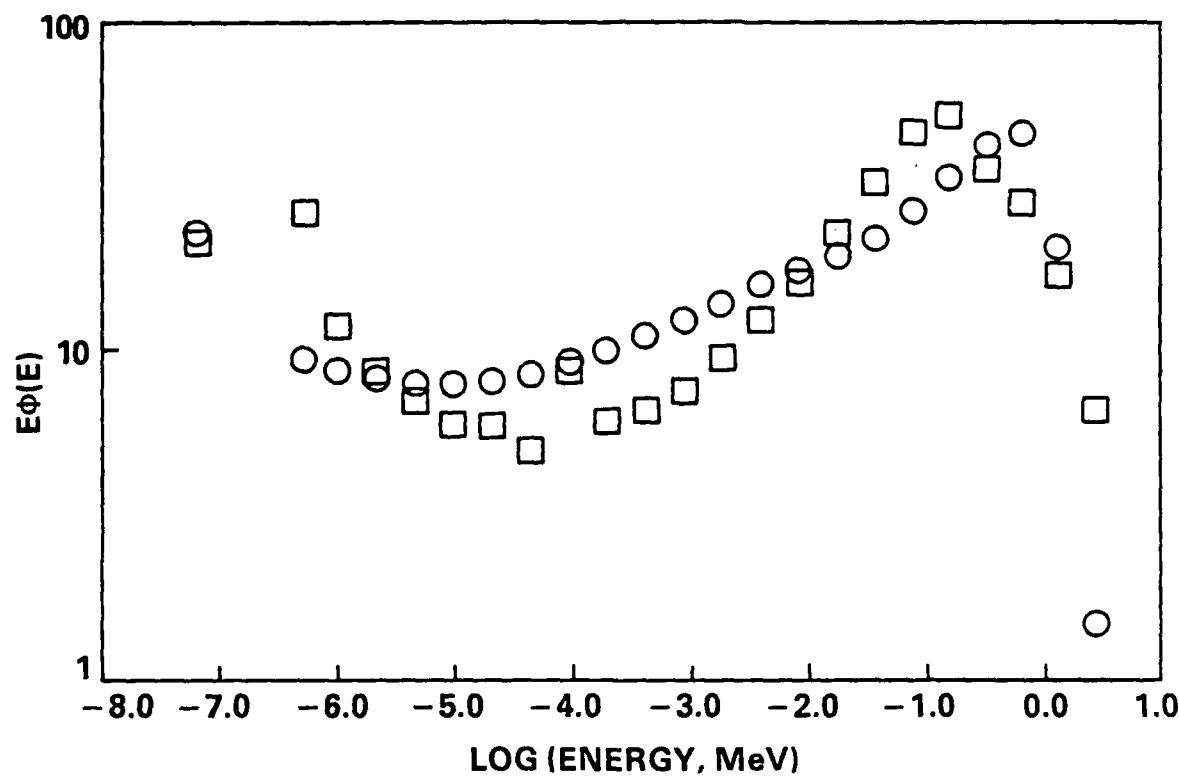
Fig. 5. Same as Fig. 4 except that MAXIET was used to determine the starting
spectrum.

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APPENDIX A

LISTING OF BUNKI COMPUTER CODE

```
00100   C                                              NOVEMBER 8,1983
00200
00300
00400   C                           BUNKI
00500
00600   C     THIS PROGRAM  CALCULATES THE PARTICLE FLUENCE,  DOSE,
00700   C     AND  DOSE EQUIVALENT SPECTRA AS A FUNCTION  OF NEUTRON
00800   C     ENERGY USING THE BON31G  OR SPUNIT UNFOLDING  CODES TO
00900   C     SOLVE THE MATRIX APPROXIMATION OF A  FREDHOLM INTEGRAL
01000   C     EQUATION OF THE FIRST  KIND.  THE TOTAL FLUENCE, DOSE,
01100   C     DOSE  EQUIVALENT, QUALITY FACTOR,  AVERAGE ENERGY, AND
01200   C     RESPONSES OF SELECTED  DETECTORS ARE  ALSO CALCULATED.
01300   C     THE INITIAL SPECTRUM  MAY BE  SPECIFIED BY THE USER OR
01400   C     A  1/E, MAXWELLIAN, INITIAL SPECTRUM MAY BE DETERMINED
01500   C     USING MAXIET,  AN ALGORITHM ORIGINALLY DEVISED FOR USE
01600   C     IN YOGI, THE ITERATIVE UNFOLDING CODE DEVELOPED AT THE
01700   C     NAVAL  RESEARCH LABORATORY.   A  MATRIX TRANSFORMATION
01800   C     ALLOWS  SMOOTHING  BIASED TO EITHER  INITIAL SPECTRUM.
01900   C
02000   C     BUNKI WAS  ORIGUNALLY  PROGRAMED AT THE NAVAL RESEARCH
02100   C     LABORATORY  IN  JULY, 1983, BY  KIMBERLY A. LOWRY  AND
02200   C     TOMMY L. JOHNSON.
02300   C
02400           PROGRAM BUNKI
02500           DOUBLE PRECISION BALL
02600           DIMENSION ALETH(12,31),SPC(31),BCE(12),CTLD(31),
02700        &  BCC(12),CRAD(31),CREM(31),CNUTRK(31),HEAD(20),
02800        &  RAD(31),REM(31),EEND(32),CE(31),SPL(32),WDLETH(31),
02900        &  CNTA(31),CA70(31),CHAN(31),SPLPLT(31,10),SPLI(32),
03000        &  SPLMAX(32),LL(12),BALL(12),PCTERR(12),CODE(12),
03100        &  PREM(31),ERRBCE(12),WHTBCE(12),A(108,31),
03200        &  SPLL(32),SS(32),BK(31,31),VECT(31)
03300   C ENERGY INTERVAL END POINTS
03400           DATA EEND/
03500        &  1.000E-08,4.140E-07,6.826E-07,1.445E-06,3.059E-06,
03600        &  6.476E-06,1.371E-05,2.902E-05,6.144E-05,1.301E-04,
03700        &  2.754E-04,5.929E-04,1.234E-03,2.613E-03,5.531E-03,
03800        &  1.171E-02,2.479E-02,5.247E-02,1.111E-01,2.237E-01,
03900        &  4.508E-01,9.072E-01,1.872E-00,3.679E-00,7.408E-00,
04000        &  1.492E+01,2.581E+01,4.465E+01,7.725E+01,1.336E+02,
04100        &  2.312E+02,4.000E+02/
04200   C NAMES OF THE DETECTORS
04300           DATA BALL/
04400        &  8HBARE     ,8HBARE+CD ,8H2 INCH  ,8H2"+CD   ,
04500        &  8H3 INCH  ,8H3"+CD   ,8H5 INCH  ,8H5"+CD   ,
04600        &  8H8 INCH  ,8H10 INCH ,8H12 INCH ,8H18 INCH /
04700   C FLUENCE TO DOSE CONVERSION FACTORS
04800           DATA CRAD/
04900        &  5.260E-10,6.088E-10,6.175E-10,6.135E-10,6.070E-10,
05000        &  6.008E-10,5.970E-10,5.937E-10,5.892E-10,5.698E-10,
05100        &  5.465E-10,5.251E-10,5.149E-10,5.083E-10,5.039E-10,
05200        &  5.629E-10,6.639E-10,7.847E-10,1.038E-09,1.454E-09,
05300        &  2.244E-09,3.406E-09,4.220E-09,5.779E-09,6.622E-09,
05400        &  9.097E-09,9.610E-09,1.013E-08,1.137E-08,1.490E-08,
05500        &  1.794E-08/
05600   C FLUENCE TO DOSE EQUIVALENT CONVERSION FACTORS
```

```
05700          DATA CREM/
05800       &  1.151E-09,1.232E-09,1.254E-09,1.244E-09,1.227L-09,
05900       &  1.211E-09,1.195E-09,1.179E-09,1.161E-09,1.123E-09,
06000       &  1.080E-09,1.040E-09,1.020E-09,1.008E-09,1.009E-09,
06100       &  1.514E-09,2.687E-09,4.775E-09,8.299E-09,1.416E-08,
06200       &  2.391E-08,3.506E-08,3.995E-08,4.072E-08,4.111E-08,
06300       &  4.356E-08,4.430E-08,4.712E-08,5.026E-08,5.536E-08,
06400       &  6.358E-08/
06500 C  FLUENCE TO NRL TLD READING CONVERSION FACTORS
06600          DATA CTLD/
06700       &  .4,.4,.4,.4,.4,.4,.4,.4,.4,.4,
06800       &  .4,.4,.395,.37,.33,.3,.27,.244,.22,.188,
06900       &  .16,.133,.11,.09,.07,.05,0,0,0,0,0/
07000 C  FLUENCE TO 'HANKINS' TLD READING CONVERSION FACTORS
07100          DATA CHAN/
07200       &  .00007,1.0,1.0,.9,.8,.75,.65,.6,.5,.46,.42,.3,
07300       &  .28,.27,.25,.24,.23,.2,.17,.13,.1,.063,.05,.028,.017,.01,
07400       &  0,0,0,0,0/
07500 C  DOSE EQUIVALENT TO NEUTRAK 144 READING CONVERSION FACTORS
07600          DATA CNUTRK/
07700       &  0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
07800       &  .33,.32,.28,.35,.66,1.0,.57,0.2,0,0,0,0,0/
07900 C  DOSE EQUIVALENT TO NTA CONVERSION FACTORS
08000          DATA CNTA/
08100       &  0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
08200       &  2.0,4.5,5.0,9.0,14.1,12.0,7.0,0,0,0,0,0/
08300 C  FLUENCE TO ANPDR-70 CONVERSION FACTORS
08400          DATA CA70/
08500       &  .0047,.0057,.0058,.0061,.0063,.0065,.0067,.0070,.0072,
08600       &  .0075,.0077,.0080,.0082,.0084,.0081,.0117,.0169,
08700       &  .0269,.0386,.0620,.1152,.1584,.2028,.1195,.0459,.0050,
08800       &  0,0,0,0,0/
08900 C  READ RESPONSE MATRICES FROM FILE 'GIANT'
09000          OPEN (UNIT=1, FILE='GIANT')
09100          READ(1,*)A
09200          CLOSE(UNIT=1,FILE='GIANT')
09300 C  COMPUTE AVERAGE ENERGY, AND LOG WIDTH OF ENERGY INTERVALS
09400          DO 1000 I=1,31
09500          CE(I)=(EEND(I)*EEND(I+1))**.5
09600 1000     WDLETH(I)=ALOG10(EEND(I+1))-ALOG10(EEND(I))
09700 C  INPUT FIXED INITIAL CONDITIONS AND DATA
09800          SLOPEJ=0
09900          PERSLP=.01
10000          THERMJ=1.0
10100          THMMIN=0.1
10200          THMMAX=10.0
10300          DEAD=.000000!32
10400          SHP=.01
10500          TSTRAT=.999
10600 C  SET OTHER INITIAL VALUES
10700          JX=1
10800          KX=1
10900          LX=1
11000          JJJ=0
11100          SPMX=1.0
11200 C  INPUT NUMBER OF ENERGY INTERVALS
11300 1010     WRITE(5,1020)
11400 1020     FORMAT(' NUMBER OF ENERGY INTERVALS?')
11500          READ(5,*)JJ
11600          IF(JJ.GE.JJJ)CHNUM='Y'
11700          JJJ=JJ+1
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11800          MM=JJ
11900   C  INPUT NUMBER AND KIND OF DETECTORS
12000   1030    IF(JX.EQ.1)GO TO 1060
12100           WRITE(5,1040)
12200   1040    FORMAT(' CHANGE DETECTORS?')
12300   1050    FORMAT(A1)
12400           READ(5,1050)CHDET
12500           IF(CHDET.EQ.'Y')GO TO 1060
12600           IF(CHDET.EQ.'N')GO TO 1140
12700           GO TO 1030
12800   1060    WRITE(5,1070)
12900   1070    FORMAT(' NUMBER OF DETECTORS?')
13000           READ(5,*)KK
13100   1080    WRITE(5,1090)
13200   1090    FORMAT(' TYPE DETECTOR CODES(? FOR HELP)')
13300           READ(5,1100)CODE(1)
13400   1100    FORMAT(A4)        .
13500           IF(CODE(1).EQ.'?')GO TO 1120
13600           READ(5,1100)(CODE(I),I=2,KK)
13700           DO 1110 I=1,KK
13800           LL(I)=0
13900           IF(CODE(I).EQ.'0')LL(I)=1
14000           IF(CODE(I).EQ.'0C')LL(I)=2
14100           IF(CODE(I).EQ.'2')LL(I)=3
14200           IF(CODE(I).EQ.'2C')LL(I)=4
14300           IF(CODE(I).EQ.'3')LL(I)=5
14400           IF(CODE(I).EQ.'3C')LL(I)=6
14500           IF(CODE(I).EQ.'5')LL(I)=7
14600           IF(CODE(I).EQ.'5C')LL(I)=8
14700           IF(CODE(I).EQ.'8')LL(I)=9
14800           IF(CODE(I).EQ.'10')LL(I)=10
14900           IF(CODE(I).EQ.'12')LL(I)=11
15000           IF(CODE(I).EQ.'18')LL(I)=12
15100           IF(LL(I).EQ.0)GO TO 1080
15200   1110    CONTINUE
15300           GO TO 1140
15400   1120    WRITE(5,1130)
15500   1130    FORMAT(10X,'0.........BARE',/,
15600       &   10X,'0C.........BARE+CADMIUM COVER',/,
15700       &   10X,'2..........2 INCH BALL',/,
15800       &   10X,'2C.........2 INCH CADMIUM COVERD BALL',/,
15900       &   10X,'3..........3 INCH BALL',/,
16000       &   10X,'3C.........3 INCH CADMIUM COVERED BALL',/,
16100       &   10X,'5..........5 INCH BALL',/,
16200       &   10X,'5C.........5 INCH CADMIUM COVERD BALL',/,
16300       &   10X,'8..........8 INCH BALL',/,
16400       &   10X,'10.........10 INCH BALL',/,
16500       &   10X,'12.........12 INCH BALL',/,
16600       &   10X,'18.........18 INCH BALL',/,/)
16700           GO TO 1080
16800   C     SELECT RESPONSE MATRIX
16900   1140    WRITE(5,1145)
17000   1145    FORMAT(' TYPE MATRIX NAME(? FOR HELP)')
17100           READ(5,1100)RMTX
17200           IF(RMTX.EQ.'?')GO TO 1150
17300           LLL=1
17400           IF(RMTX.EQ.'SAN4')LLL=0
17500           IF(RMTX.EQ.'SAN1')LLL=12
17600           IF(RMTX.EQ.'M60')LLL=24
17700           IF(RMTX.EQ.'M65')LLL=36
17800           IF(RMTX.EQ.'MS13')LLL=48
17900           IF(RMTX.EQ.'LOGN')LLL=60
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18000          IF(RMTX.EQ.'BARC')LLL=72
18100          IF(RMTX.EQ.'UTA4')LLL=84
18200          IF(RMTX.EQ.'UTA1')LLL=96
18300          IF(LLL.EQ.1)GO TO 1140
18400          GO TO 1160
18500  1150    WRITE(5,1155)
18600  1155    FORMAT(10X,'SAN4......SANNA 4MM X 4MM ',/,
18700      &   10X,'SAN13.....SANNA 13MM X 13MM ',/,
18800      &   10X,'M60.......M60',/,
18900      &   10X,'M65.......M65',/,
19000      &   10X,'MS13......MODIFIED SANNA 13MMX13MM',/,
19100      &   10X,'LOGNM.....LOGNORMAL ',/,
19200      &   10X,'BARC......BHABA MONTE CARLO '/,
19300      &   10X,'UTA4......4MM X 4MM U OF TEXAS ',/,
19400      &   10X,'UTA13.....13MM X 13MM U OF TEXAS ',/)
19500          GO TO 1140
19600  C     SELECT UNFOLDING CODE
19700  1160    WRITE(5,1165)
19800  1165    FORMAT(' TYPE UNFOLDING CODE(? FOR HELP)')
19900          READ(5,1100)UNFOLD
20000          IF(UNFOLD.EQ.'?')GO TO 1170
20100          IF(UNFOLD.EQ.'BON3'.OR.UNFOLD.EQ.'SPUN')GO TO 1180
20200          GO TO 1160
20300  1170    WRITE(5,1175)
20400  1175    FORMAT(10X,'BON31G.......HASL UNFOLDING CODE',/,
20500      &   10X,'SPUNIT.......PNL-SOVIET UNFOLDING CODE',/)
20600          GO TO 1160
20700  1180    CONTINUE
20800  C  SELECT APPROPRIATE COLUMNS FROM MATRIX AND ADJUST
20900  C  MATRIX TO UNFOLD PER UNIT LETHARGY
21000          DO 1190  I=1,KK
21100          L=LL(I)+LLL
21200          DO 1190 J=1,JJJ
21300  1190    ALETH(I,J)=A(L,J)*WDLETH(J)
21400  C INPUT VARIABLE INITIAL CONDITIONS AND DATA
21500  1200    WRITE(5,1210)
21600  1210    FORMAT(' PUT SPECTRA IN FILE FOR PLOTTING?')
21700          READ(5,1050)FILE
21800  1220    IF(FILE.EQ.'Y')GO TO 1230
21900          IF(FILE.EQ.'N')GO TO 1250
22000          GO TO 1200
22100  1230    WRITE(5,1240)
22200  1240    FORMAT(' FILE NUMBER OF THE SPECTRUM? (1 TO 10)')
22300          READ(5,*)KX
22400          IF(KX.LT.1.OR.KX.GT.10)GO TO 1230
22500  1250    IF(JX.EQ.1)GO TO 1270
22600          WRITE(5,1260)
22700  1260    FORMAT(' CHANGE THE HEADING?')
22800          READ(5,1050)CHHEAD
22900          IF(CHHEAD.EQ.'Y')GO TO 1270
23000          IF(CHHEAD.EQ.'N')GO TO 1320
23100          GO TO 1250
23200  1270    WRITE (5,1280)
23300  1280    FORMAT(' TYPE THE HEADING (<80 CHARACTERS)')
23400          READ(5,1290)(HEAD(I),I=1,20)
23500  1290    FORMAT(20A4)
23600  1320    WRITE(5,1330)
23700  1330    FORMAT(' SEARCH FOR MAXWELLIAN, 1/E INITIAL SPECTRUM?')
23800          READ(5,1050)SRHMA
23900          IF(SRHMA.NE.'Y'.AND.SRHMA.NE.'N')GO TO 1320
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24000            IF(SRHMA.NE.SRHMAX)LX=1
24100            SRHMAX=SRHMA
24200            IF(SRHMAX.EQ.'Y')GO TO 1380
24300            IF(SRHMAX.EQ.'N')GO TO 1340
24400            GO TO 1320
24500     1340   IF(LX.EQ.1)GO TO 1360
24600            IF(CHNUM.EQ.'Y')GO TO 1360
24700            WRITE(5,1350)
24800     1350   FORMAT(' CHANGE INITIAL SPECTRUM?')
24900            READ(5,1050)CHISPC
25000            IF(CHISPC.EQ.'Y')GO TO 1360
25100            IF(CHISPC.EQ.'N')GO TO 1480
25200            GO TO 1340
25300     1360   WRITE(5,1370)JJJ
25400     1370   FORMAT(' TYPE INITIAL SPECTRUM (',I2,' VALUES)')
25500            READ(5,*)(SPLI(I),I=1,JJJ)
25600            GO TO 1480
25700     1380   IF(LX.EQ.1)GO TO 1400
25800            WRITE(5,1390)
25900     1390   FORMAT(' CHANGE MAXWELLIAN TEMP, SHAPE, OR PERTURBATION?')
26000            READ(5,1050)CHTEMP
26100            IF(CHTEMP.EQ.'Y')GO TO 1400
26200            IF(CHTEMP.EQ.'N')GO TO 1480
26300            GO TO 1380
26400     1400   WRITE(5,1410)
26500     1410   FORMAT(' TYPE MAXWELLIAN TEMP, SHAPE, AND PERTURBATION')
26600            READ(5,*)TEMPIJ,SHAPE,PERTMP
26700     1480   IF(JX.EQ.1)GO TO 1500
26800            WRITE(5,1490)
26900     1490   FORMAT(' CHANGE FIT PARAMETERS?')
27000            READ(5,1050)CHFIT
27100            IF(CHFIT.EQ.'Y')GO TO 1500
27200            IF(CHFIT.EQ.'N')GO TO 1520
27300            GO TO 1480
27400     1500   WRITE(5,1510)
27500     1510   FORMAT(' TYPE: END TEST(%),',
27600        &   /,'       SMOOTHING FACTOR, ',
27700        &   /,'       CALIBRATION FACTOR, ',
27800        &   /,'       ITERATIONS BEFORE ERROR TEST, ',
27900        &   /,'       AND MAXIMUM NUMBER OF ITERATIONS')
28000            READ(5,*)TSTPER,SMO,CAL,ITRTST,ITRMAX
28100            PERTHM=1.0+20*PERSLP
28200            PERE=1.0+10*PERSLP
28300            IF(SRHMAX.EQ.'N'.AND.ITRMAX.EQ.0)GO TO 1820
28400            TSTPER=(KK*TSTPER**2)/10000
28500     1520   TEMPI=TEMPIJ
28600            SLOPEI=SLOPEJ
28700            THERMI=THERMJ
28800            IF(JX.EQ.1)GO TO 1540
28900            IF(CHDET.EQ.'Y')GO TO 1540
29000     1525   WRITE(5,1530)
29100     1530   FORMAT(' CHANGE BALL DATA?')
29200            READ(5,1050)CHBCE
29300            IF(CHBCE.EQ.'Y')GO TO 1540
29400            IF(CHBCE.EQ.'N')GO TO 1590
29500            GO TO 1525
29600     1540   DO 1560 I=1,KK
29700            L=LL(I)
29800            WRITE(5,1550)BALL(L)
29900     1550   FORMAT(' TYPE ',A8,'BONNER SPHERE COUNT, % ERROR')
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30000   1560    READ(5,*)(BCE(I),ERRBCE(I))
30100   C  SUM ERRORS, MAKE DEAD TIME CORRECTION TO BALL COUNTS
30200           SUMWHT=0
30300           DO 1570 I=1,KK
30400           SUMWHT=SUMWHT+ERRBCE(I)
30500   1570    BCE(I)=BCE(I)/(1.0-BCE(I)*DEAD)
30600   C  CALCULATE BALL COUNT ERROR WEIGHTS
30700           DO 1580 I=1,KK
30800   1580    WHTBCE(I)=SUMWHT/(KK*ERRBCE(I))
30900   C  CALCULATE MAXWELLIAN, 1/E SPECTRUM IF REQUIRED
31000   1590    IF(SRHMAX.EQ.'N')GO TO 1820
31100   C  BEGINNING OF MAXIET ALGORITHM
31200   C      INITIALIZE FIT PARAMETERS
31300           ERRORE=123456789
31400           TEMP=TEMPI
31500           ERRORM=ERRORE
31600   1600    SLOPE=SLOPEI
31700           THERM=THERMI
31800   C      CALCULATE MAXWELLIAN SPECTRUM
31900           SPMX=0
32000           DO 1610 I=1,JJJ
32100           SPLMAX(I)=(CE(I)**1.5)*(EXP(-CE(I)/TEMP))
32200           IF(SPLMAX(I).GT.SPMX)SPMX=SPLMAX(I)
32300           IF(SPMX.EQ.SPLMAX(I))GO TO 1610
32400           SPLMAX(I)=SPMX**SHAPE*SPLMAX(I)**(1.0-SHAPE)
32500           IF(SPLMAX(I).LT.SPLMAX(I-1)*SHP)SPLMAX(I)=SPLMAX(I-1)*SHP
32600   1610    CONTINUE
32700   C      CALCULATE 1/E INITIAL SPECTRUM
32800           ERROR=123456789
32900           ERRORE=123456789
33000           HGTE=SPMX*PERE
33100   1620    ERRORT=ERROR
33200   1630    HGTE=HGTE/PERE
33300   1640    DO 1650 I=1,JJJ
33400   1650    SPLI(I)=HGTE*CE(I)**SLOPE
33500   C      COMBINE MAXWELLIAN AND 1/E SPECTRA
33600           DO 1660 I=1,JJJ
33700           IF(SPLI(I).LT.SPLMAX(I))GO TO 1670
33800           SPLI(I)=(SPLI(I)+SPLMAX(I))*0.5
33900   1660    CONTINUE
34000           GO TO 1630
34100   1670    DO 1680 J=I,JJJ
34200   1680    SPLI(J)=SPLMAX(J)
34300   C      ADJUST THERMAL ENERGY BIN
34400           SPLI(1)=SPLI(2)*THERM
34500   C  CALCULATE SPHERE RESPONSES AND SUM FROM SPECTRUM
34600           DO 1690 M=1,KK
34700           BCC(M)=0
34800           DO 1690 J=1,JJJ
34900   1690    BCC(M)=BCC(M)+ALETH(M,J)*SPLI(J)
35000   C  CALCULATE SUMS OF SPHERE DATA
35100           SUMBCE=0
35200           SUMBCC=0
35300           DO 1700 I=1,KK
35400           SUMBCE=SUMBCE+BCE(I)
35500   1700    SUMBCC=SUMBCC+BCC(I)
35600   C  NORMALIZE CALCULATED SPHERE RESPONSES
35700   C  TO EXPERIMENTAL DATA
35800           RNORM=SUMBCE/SUMBCC
35900           DO 1710 I=1,KK
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36000   1710    BCC(I)=BCC(I)*RNORM
36100   C       CALCULATE ERROR ON FIT
36200           ERROR=0
36300           DO 1720 I=1,KK
36400           ERR=(BCC(I)-BCE(I))/BCE(I)
36500   1720    ERROR=ERROR+WHTBCE(I)*ERR*ERR
36600           IF(ERROR.LT.ERRORT)GO TO 1620
36700           HGTE=HGTE*PERE
36800   1730    IF(ERRORT.GE.ERRORE)GO TO 1740
36900   C       SAVE BEST VALUES OF FIT PARAMETERS
37000           ERRORE=ERRORT
37100           HGTEE=HGTE
37200           THERME=THERM
37300           SLOPEE=SLOPE
37400           MX=0
37500   C       CHANGE SLOPE
37600   1740    SLOPE=SLOPE+PERSLP
37700           IF(MX.EQ.1)SLOPE=SLOPEE
37800   C       CHANGE THERMAL BIN
37900           THERM=THERME*PERTHM
38000           IF(THERM.GE.THMMAX)GO TO 1750
38100           IF(MX.EQ.0)THERM=THERME
38200           MX=MX+1
38300           IF(MX.GT.10)GO TO 1750
38400           HGTE=HGTE*PERE*(1.0+10*PERSLP)
38500           IF(MX.EQ.1)HGTE=HGTEE*PERE*PERTHM
38600   C       RESET ERROR, SEARCH FOR BETTER FIT PARAMETERS
38700           ERRORT=123456789
38800           GO TO 1640
38900   C       CALCULATE ERROR ON FIT
39000   1750    PERROR=100*(ERRORE/KK)**.5
39100   C       WRITE BEST VALUES OF FIT PARAMETERS TO TERMINAL
39200           WRITE(5,*)TEMP,SHAPE,HGTEE,SLOPEE,THERME,PERROR
39300           IF(ERRORE.GE.ERRORM)GO TO 1760
39400   C       SAVE BEST VALUES OF FIT PARAMETERS
39500           TEMPM=TEMP
39600           HGTEM=HGTEE
39700           THERMM=THERME
39800           SLOPEM=SLOPEE
39900           ERRORM=ERRORE
40000   C       CHANGE MAXWELLIAN TEMPERATURE IF REQUIRED
40100           IF(PERTMP.EQ.0)GO TO 1760
40200           TEMP=TEMP-PERTMP
40300   C       RETURN AND SEARCH FOR BETTER PARAMETERS IF
40400   C       MAXWELLIAN TEMP IS IN RANGE
40500           IF(TEMP.GT.PERTMP)GO TO 1600
40600   1760    CONTINUE
40700   C       IF FINAL PARAMETERS EQUAL INITIAL PARAMETERS CAHNGE
40800   C       INITIAL PARAMETERS AND CONTINUE SEARCH
40900           A1=0
41000           IF(SLOPEM.EQ.SLOPEI)A1=1
41100           A2=0
41200           IF(THERMM.EQ.THERMI.AND.THERMI.GE.THMMIN)A2=1
41300           A3=0
41400           IF(TEMPM.EQ.TEMPI.AND.TEMPM.LT.TEMPIJ+10*PERTMP)A3=1
41500           IF(PERTMP.EQ.0)A3=0
41600           IF(A1.EQ.1)SLOPEI=SLOPEI-10*PERSLP
41700           IF(A2.EQ.1)THERMI=THERMI/PERTHM**3
41800           IF(A3.EQ.1)TEMPI=TEMPI+3*PERTMP
41900           IF(A1+A2+A3.GT..5)GO TO 1590
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42000    C     IF NOT, CALCULATE INITIAL SPECTRUM WITH BEST PARAMETERS
42100          SPMX=0
42200          DO 1770 I=1,JJJ
42300          SPLMAX(I)=(CE(I)**1.5)*(EXP(-CE(I)/TEMPM))
42400          IF(SPLMAX(I).GT.SPMX)SPMX=SPLMAX(I)
42500          IF(SPMX.EQ.SPLMAX(I))GO TO 1770
42600          SPLMAX(I)=SPMX**SHAPE*SPLMAX(I)**(1.0-SHAPE)
42700          IF(SPLMAX(I).LT.SPLMAX(I-1)*SHP)SPLMAX(I)=SPLMAX(I-1)*SHP
42800    1770  CONTINUE
42900          DO 1780 I=1,JJJ
43000    1780  SPLI(I)=HGTEM*CE(I)**SLOPEM
43100          DO 1790 I=1,JJJ
43200          IF(SPLI(I).LT.SPLMAX(I))GO TO 1800
43300          SPLI(I)=(SPLI(I)+SPLMAX(I))*0.5
43400    1790  CONTINUE
43500    1800  DO 1810 J=I,JJJ
43600    1810  SPLI(J)=SPLMAX(J)
43700          SPLI(1)=SPLI(2)*THERMM
43800    C  COMPLETION OF MAXIET ALGORITHM
43900    C  TRANSFORM MATRIX TO CONSTANT INITIAL SPECTRUM
44000    1820  DO 1825 I=1,JJJ
44100          DO 1825 K=1,KK
44200    1825  ALETH(K,I)=ALETH(K,I)*SPLI(I)
44300          DO 1830 I=1,JJJ
44400    1830  SPL(I)=1
44500    C  CALCULATE SPHERE RESPONSES AND SUM FROM INITIAL SPECTRUM
44600          DO 1840 M=1,KK
44700          BCC(M)=0
44800          DO 1840 J=1,JJ
44900    1840  BCC(M)=BCC(M)+ALETH(M,J)*SPL(J)
45000          IF(SRHMAX.EQ.'N'.AND.ITRMAX.EQ.0)GO TO  2000
45100    C  NORMALIZE CALCULATED SPHERE RESPONSES AND INITIAL
45200    C  SPECTRUM TO EXPERIMENTAL DATA
45300          SUMBCC=0
45400          SUMBCE=0
45500          DO 1850 I=1,KK
45600          SUMBCE=SUMBCE+BCE(I)
45700    1850  SUMBCC=SUMBCC+BCC(I)
45800          RNORM=SUMBCE/SUMBCC
45900          DO 1860 I=1,KK
46000    1860  BCC(I)=BCC(I)*RNORM
46100          SUMBCC=SUMBCE
46200          DO 1870 I=1,JJJ
46300          SPL(I)=SPL(I)*RNORM
46400    1870  CONTINUE
46500    C   CALCULATE ERROR ON FIT
46600          ERROR=0
46700          DO 1880 I=1,KK
46800          ERR=(BCC(I)-BCE(I))/BCE(I)
46900    1880  ERROR=ERROR+WHTBCE(I)*ERR*ERR
47000          IF(ITRMAX.EQ.0)GO TO 2000
47100          ITER=0
47200    1890  ERRORU=ERROR
47300    C  SELECT UNFOLDING ALGORITHM
47400          IF(UNFOLD.EQ.'BON3')GO TO 1945
47500    C  BEGINNING OF SPUNIT UNFOLDING ALGORITHM
47600          IF(ITER.GT.0)GO TO 1905
47700          DO 1900 J=1,JJ
47800          SS(J)=0
47900          DO 1900 I=1,KK
```

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48000   1900    SS(J)=SS(J)+ALETH(I,J)/BCE(I)
48100   1905    DO 1940 K=1,ITRTST
48200           ITER=ITER+1
48300           DO 1910 J=1,JJ
48400           SPLL(J)=0
48500           DO 1910 I=1,KK
48600   1910    SPLL(J)=SPLL(J)+(SPL(J)*ALETH(I,J)/(SS(J)*BCC(I)))
48700           DO 1920 J=3,MM
48800   1920    SPL(J)=(SPLL(J-1)*SMO+SPLL(J)+SPLL(J+1)*SMO)/(1+2*SMO)
48900           SPL(1)=SPLL(1)
49000           SPL(2)=SPLL(2)
49100           IF(MM.EQ.JJ)GO TO 1925
49200           SPL(JJ)=SPLL(JJ)
49300   1925    DO 1930 M=1,KK
49400           BCC(M)=0
49500           DO 1930 J=1,JJ
49600   1930    BCC(M)=BCC(M)+ALETH(M,J)*SPL(J)
49700   1940    CONTINUE
49800   C   END OF*SPUNIT UNFOLDING ALGORITHM
49900           GO TO 1990
50000   C   BEGINNING OF BON31G UNFOLDING ALGORITHM
50100   1945    IF(ITER.GT.0)GO TO 1960
50200           DO 1950 I=1,JJ
50300           DO 1950 J=1,JJ
50400           BK(J,I)=0
50500           DO 1950 M=1,KK
50600   1950    BK(J,I)=BK(J,I)+ALETH(M,J)*ALETH(M,I)
50700           DO 1955 I=1,JJ
50800           VECT(I)=0
50900           DO 1955 J=1,KK
51000   1955    VECT(I)=VECT(I)+ALETH(J,I)*BCE(J)
51100   1960    DO 1980 N=1,ITRTST
51200           ITER=ITER+1
51300           DO 1970 J=1,JJ
51400           AX=0.
51500           DO 1965 M=1,JJ
51600   1965    AX=SPL(M)*BK(J,M)+AX
51700   1970    SPLL(J)=SPL(J)*VECT(J)/AX
51800           DO 1975 J=3,MM
51900   1975    SPL(J)=(SPLL(J-1)*SMO+SPLL(J)+SPLL(J+1)*SMO)/(1+2*SMO)
52000           SPL(1)=SPLL(1)
52100           SPL(2)=SPLL(2)
52200           IF(MM.EQ.JJ)GO TO 1980
52300           SPL(JJ)=SPLL(JJ)
52400   1980    CONTINUE
52500           DO 1985 M=1,KK
52600           BCC(M)=0
52700           DO 1985 J=1,JJ
52800   1985    BCC(M)=BCC(M)+ALETH(M,J)*SPL(J)
52900   C   END OF BON31G UNFOLDING ALGORITHM
53000   1990    CONTINUE
53100   C   CALCULATE ERROR ON FIT
53200           ERROR=0
53300           DO 1995 I=1,KK
53400           ERR=(BCC(I)-BCE(I))/BCE(I)
53500   1995    ERROR=ERROR+WHTBCE(I)*ERR*ERR
53600   C   TEST FOR COMPLETION, CONTINUE IF NOT COMPLETE
53700           IF(ERROR/ERRORU.LT.TSTRAT.AND.ITER+ITRTST.LE.ITRMAX
53800       &   .AND.ERROR.GT.TSTPER)GO TO 1890
53900   C   IF COMPLETE, DO INVERSE TRANSFORM OF SPECTRUM AND MATRIX
```

```
54000    2000     DO 2005 I=1,JJJ
54100    2005     SPL(I)=SPL(I)*SPLI(I)
54200             DO 2010 I=1,KK
54300             DO 2010 J=1,JJJ
54400    2010     ALETH(1,J)=ALETH(I,J)/SPLI(J)
54500    C   CALCULATE OUTPUT VALUES
54600             IF(SRHMAX.EQ.'N'.AND.ITRMAX.EQ.0)GO TO 2030
54700    2015     HGTEM=0.5*HGTEM/SPMX
54800             SUMERR=0
54900             DO 2020 I=1,KK
55000             PCTERR(I)=100*(BCC(I)-BCE(I))/BCE(I)
55100    2020     SUMERR=SUMERR+PCTERR(I)*PCTERR(I)
55200             PERROR=(SUMERR/KK)**.5
55300    2030     SUMSPC=0
55400             SUMRAD=0
55500             SUMREM=0
55600             SUMEXS=0
55700             SUMTLD=0
55800             SUMHAN=0
55900             SUMNTR=0
56000             SUMNTA=0
56100             SUMA70=0
56200             DO 2035 I=1,31
56300             IF(I.GT.JJ)SPL(I)=0
56400             SPL(I)=SPL(I)*CAL
56500             SPLPLT(I,KX)=SPL(I)
56600             SPC(I)=SPL(I)*WDLETH(I)
56700             SUMSPC=SUMSPC+SPC(I)
56800             REM(I)=CREM(I)*SPC(I)
56900             SUMREM=SUMREM+REM(I)
57000             RAD(I)=CRAD(I)*SPC(I)
57100             SUMRAD=SUMRAD+RAD(I)
57200             SUMEXS=SUMEXS+CE(I)*SPC(I)
57300             SUMTLD=SUMTLD+CTLD(I)*SPC(I)
57400             SUMHAN=SUMHAN+CHAN(I)*SPC(I)
57500             SUMNTR=SUMNTR+CNUTRK(I)*REM(I)
57600             SUMNTA=SUMNTA+CNTA(I)*REM(I)
57700    2035     SUMA70=SUMA70+CA70(I)*SPC(I)
57800             QF=SUMREM/SUMRAD
57900             AVEEN=(SUMEXS-CE(1)*SPC(1))/(SUMSPC-SPC(1))
58000             SUMTLD=(SUMTLD/SUMREM)/4.064E+06
58100             SUMHAN=(SUMHAN/SUMREM)/2.085E+06
58200             SUMNTR=(SUMNTR/SUMREM)/.5748
58300             SUMNTA=(SUMNTA/SUMREM)/8.033
58400             SUMA70=(SUMA70/SUMREM)/4.755E+06
58500             DO 2040 I=1,JJ
58600    2040     PREM(I)=100*(REM(I)/SUMREM)
58700    C   SET UNCOMPUTED PARAMETERS TO 0, WRITE PARAMETERS TO TERMINAL
58800             IF(SRHMAX.EQ.'N')THERMM=0
58900             IF(SRHMAX.EQ.'N')TEMPM=0
59000             IF(SRHMAX.EQ.'N')HGTEM=0
59100             IF(SRHMAX.EQ.'N')SLOPEM=0
59200             IF(SRHMAX.EQ.'N'.AND.ITRMAX.EQ.0)PERROR=0
59300             IF(ITRMAX.EQ.0)ITER=0
59400             WRITE(5,*)TEMPM,SHAPE,HGTEM,SLOPEM,THERMM,PERROR,ITER
59500    C   DECIDE IF RESULTS ARE WORTH KEEPING
59600    2045     WRITE(5,2050)
59700    2050     FORMAT(' SAVE THESE RESULTS?')
59800             READ(5,1050)SAVE
59900             IF(SAVE.EQ.'N')GO TO 2190
```

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```
60000           IF(SAVE.EQ.'Y')GO TO 2055
60100           GO TO 2045
60200    C  WRITE RESULTS TO DISC
60300    2055    WRITE(1,2060)(HEAD(I),I=1,20)
60400    2060    FORMAT('1',20A4)
60500           IF(ITRMAX.EQ.0)GO TO 2080
60600           WRITE(1,2070)RMTX,UNFOLD,TEMPM,SHAPE,CAL,SMO,PERROR,ITER
60700    2070    FORMAT(1X,/,4X,'RESPONSE  UNFOLD   MAXWELL     CALIB.
60800         &    SMOOTH    PER CENT  NO. OF',/,
60900         &  4X,'MATRIX   CODE     TEMP,SHAPE FACTOR    FACTOR     ERROR
61000         &    ITERATIONS',
61100         &  /,1X,A8,A10,F8.2,',',F4.2,F8.4,2(F10.4),I8)
61200           GO TO 2100
61300    2080    WRITE(1,2090) RMTX,TEMPM,SHAPE,HGTEM,SLOPEM,THERMM,PERROR,CAL
61400    2090    FORMAT(1X,/,4X,'RESPONSE  MAXWELL     1/E X      LETH
61500         &       THERMAL    PERCENT   CALIB.',/,
61600         &  4X,'MATRIX    TEMP,SHAPE FACTOR     SLOPE      FACTOR     ERROR
61700         &   FACTOR',
61800         &  /,1X,A8,F9.2,',',F4.2,F8.4,4(F10.4))
61900    2100    WRITE(1,2110)
62000    2110    FORMAT(1X/10X,9HDETECTORS,10X,8HMEASURED,5X,
62100         &  12H  CALCULATED,5X,7HPERCENT,/
62200         &  30X,6HCOUNTS,10X,6HCOUNTS,6X,10HDIFFERENCE)
62300           DO 2120 I=1,KK
62400           L=LL(I)
62500    2120    WRITE(1,2130),BALL(L),BCE(I),BCC(I),PCTERR(I)
62600    2130    FORMAT(10X,A10,1X,0PF15.3,0PF16.3,0PF15.3)
62700           WRITE(1,2140) SUMSPC,AVEEN,SUMRAD,SUMREM,QF,SUMTLD,SUMHAN,
62800         &  SUMNTR,SUMNTA,SUMA70
62900    2140    FORMAT(/,
63000         &  10X,'TOTAL FLUENCE=',T34,1PE11.3,T48,'NEUTRONS/CM2',/,
63100         &  10X,'AVE ENERGY(LESS TH)=',T34,1PE11.3,T48,'MEV',/,
63200         &  10X,'DOSE=',T34,1PE11.3,T48,'RAD',/,
63300         &  10X,'DOSE EQUIVALENT=',T34,1PE11.3,T48,'REM',/,
63400         &  10X,'QUALITY FACTOR=',T34,0PF7.3,T48,'REM/RAD',/,
63500         &  10X,'NRL TLD RESPONSE=',T34,F7.3,T48,'REM/REM(CF-252)',/,
63600         &  10X,'"HANKINS"TLD RESPONSE=',T34,F7.3,T48,'REM/REM(CF-252)',/,
63700         &  10X,'NEUTRAK RESPONSE=',T34,F7.3,T48,'REM/REM(CF-252)',/,
63800         &  10X,'NTA RESPONSE=',T34,F7.3,T48,'REM/REM(CF-252)',/,
63900         &  10X,'ANPDR-70 RESPONSE=',T34,F7.3,T48,'REM/REM(CF-252)',/)
64000           WRITE(1,2150)
64100    2150    FORMAT(3X,
64200         &  ' BIN   ENERGY    FLUENCE    FLUENCE
64300         &   DOSE       DOSE EQV.  DOSE EQV.',/,
64400         &  '   NO.   MAX (MEV)  NEUT/CM2
64500         &   N/CM2/LETH (RAD)      (REM)     (% OF TOTAL)')
64600           DO 2160 I=1,JJ
64700    2160    WRITE(1,2170) I,EEND(I+1),SPC(I),SPL(I),RAD(I),
64800         &  REM(I),PREM(I)
64900    2170    FORMAT(2X,I4,2X,6(1PE11.3))
65000           WRITE(1,2180)
65100    2180    FORMAT(1X,/,/)
65200    2190    CONTINUE
65300    C  SET FLAGS, RETURN FOR ANOTHER SPECTRUM IF DESIRED
65400           JX=0
65500           LX=0
65600           CHDET='N'
65700           CHNUM='N'
65800    2200    WRITE(5,2210)
65900    2210    FORMAT(' LAST SPECTRUM?')
```

```
66000          READ(5,1050)LASTSP
66100          IF(LASTSP.EQ.'N')GO TO 2220
66200          IF(LASTSP.EQ.'Y')GO TO 2240
66300          GO TO 2200
66400  2220    WRITE(5,2230)
66500  2230    FORMAT(' CHANGE MATRIX, DETECTORS, UNFOLDING CODE',/,
66600      &   ' AND/OR ENERGY INTERVALS?')
66700          READ(5,1050)CHMTX
66800          IF(CHMTX.EQ.'N')GO TO 1220
66900          IF(CHMTX.EQ.'Y')GO TO 1010
67000          GO TO 2220
67100  2240    IF(FILE.EQ.'N')GO TO 2250
67200  C  WRITE SPECTRA TO FILE FOR PLOTTING IF REQUIRED
67300          OPEN(UNIT=1,FILE='SPECX')
67400          WRITE(1,*)SPLPLT
67500          CLOSE(UNIT=1,FILE='SPECX')
67600  2250    END
```

APPENDIX B

Description of Input Parameters of BUNKI

SLOPEJ (9800,38600)   The initial value of the slope of the 1/E part of the
         MAXIET spectrum. Usually 0.

PERSLP (9900,37600,28600,38400,41600)   The amount by which the slope of the
         1/E part of the MAXIET spectrum is changed in searching for a better
         fit to the data. Typical values, 0.005 - 0.02.

THERMJ (10000,28700)   The initial value of the thermal bin of the initial
         MAXIET spectrum. Usually 1.0.

THMMIN (10100,41200)   The minimum value allowable for the thermal bin of the
         MAXIET spectrum.

THMMAX (10200,38000)   The maximum allowable value for the thermal bin of the
         MAXIET spectrum. THMMAX and THMMIN are set from physical characteristics
         of the radiation environment.

DEAD (10300,30500)   The dead time of the instrument used to determine the
         detector counts.

SHP (10400,32500,42700)   The minimum value of the (I+1) bin relative to the
         I bin for the initial MAXIET spectrum. Used to limit the high energy
         roll-off of the calculated Maxwellian spectrum.

TSTRAT (10500,53700)   The maximum allowable value of the error on the fit
         relative to the value when the error was last tested. Prevents
         further iterations when no significant improvement in fit is
         occurring with further iterations. If set > 1.0 this test will
         not terminate the fit. Typical values: 0.9, 0.99, 0.999, 0.9999, 1.1.

TEMPIJ (25900-26600,28500,41400)   The initial guess of the temperature of
         the Maxwellian peak. Program asks for "Maxwellian Temp.".

SHAPE (25900-26600, 36400,42600)   The shape of the high temperature portion
         of the Maxwellian peak. Typical values, 0-0.5. Originally the
         program searched for the best shape, but this feature was considered
         unnecessary and is now user input. Program asks for "shape".

PERTMP (25900-26600, 40100,40200,40500,41400,41500,41800)   The amount by
         which the Maxwellian temperature is changed in searching for a
         better fit to the data. Should be approximately 10% the Maxwellian
         temperature, TEMPIJ. May be positive, negative, or zero. Positive
         searches for a lower temperature, negative for a higher temperature.
         If set to zero, the fit is forced from TEMPIJ which is often a
         useful feature. Program asks for "perturbation".

TSTPER (26900-28000,28400,53800)   An end test used to terminate the fit.
         When the error on the fit drops below this error the fit is
         terminated. Program asks for "end test (%)".

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SMO (26900-28000, 48800,51900)   The smoothing factor.   Typical values,
        0-0.05.   Smoothing increases with increasing SMO.   Program asks
        for "smoothing factor".

CAL (26900-28000, 56400,60600)   A calibration factor used to correct the
        spectrum to agree with some calibration standard.   Typical values
        we have found for a 4 mm x 4 mm crystal and the Sanna matrix are
        1.2-1.6 for Cf-252.   Program asks for "calibration factor".

ITRTST (26900-28000, 48100,51100,53700)   The number of iterations before
        making a test to decide if the fit should be terminated.   Typical
        values, 1-100.   Program asks for "iterations before error test".

ITRMAX (26900-28000, 45000,47000,53700,54600,59200,59300,60500)   The
        maximum number of iterations allowed.   Typically 100-1000.   May
        also be set to 0.   If the user inputs the initial spectrum and
        ITRMAX=0 the program does not ask for detector data but calculates
        the output parameters directly from the input spectrum.   This
        option is useful for calculating integral parameters from known
        spectra.   If using the MAXIET algorithm, setting ITRMAX=0 prevents
        any further fitting of the data by either SPUNIT or BON31G.   The
        MAXIET spectrum, and calculated integral parameters, are then output
        in a slightly different format than that shown in Appendix D.
        Program asks for "maximum number of iterations".

PERTHM (28100,37900,38500,41700)   The amount by which the thermal bin of
        the MAXIET spectrum is changed in searching for a better fit to
        the data.   PERTHM is not input directly, but is calculated from
        PERSLP.

PERE (28200,33000,33200,36700,38400,38500)   The amount by which the
        magnitude of the 1/E part of the MAXIET spectrum is changed in
        searching for a better fit to the data.   PERE is not input directly,
        but is calculated from PERSLP.   A reasonable relationship between
        PERSLP, PERTHM, and PERE must be maintained to insure that the
        MAXIET algorithm will find the best fit to the detector data.

```
.LOGIN 720,1564
JOB 32 RNL-603A-DUAL-KI-54 TTY127
[LGNJSP Other jobs same PPN:63]
[LGNRDU Recomputing disk usage]
[LGNQTA DSKU IN:3000 OUT:3000 USED:1605]
1510    17-Feb-84       Fri
[No mail]

.EX BUNKI.FOR
LINK:   Loading
[LNKXCT BUNKI execution]


NUMBER OF ENERGY INTERVALS?
25
NUMBER OF DETECTORS?
7
TYPE DETECTOR CODES (? FOR HELP)
0
2C
3C
5
8
10
12
TYPE MATRIX NAME (? FOR HELP)
SAN4
TYPE UNFOLDING CODE (? FOR HELP)
SPUNIT
PUT SPECTRA IN FILE FOR PLOTTING?
N
TYPE THE HEADING (<80 CHARACTERS)
        CF 252 in 60 CM STEEL BALL + 1.27 CM LUCITE
SEARCH FOR MAXWELLIAN, 1/E INITIAL SPECTRUM?
N
TYPE INITIAL SPECTRUM(26 VALUES)
26*1
TYPE: END TEST(%),
      SMOOTHING FACTOR,
      CALIBRATION FACTOR,
      ITERATIONS BEFORE ERROR TEST,
      AND MAXIMUM NUMBER OF ITERATIONS
.2,0,1,25,1000
TYPE BARE     BONNER SPHERE COUNT, % ERROR
935,3
TYPE 2"+CD    BONNER SPHERE COUNT, % ERROR
2125,1
TYPE 3"+CD    BONNER SPHERE COUNT, % ERROR
5197,1
TYPE 5 INCH   BONNER SPHERE COUNT, % ERROR
8361,1
TYPE 8 INCH   BONNER SPHERE COUNT, % ERROR
4547,1
```

```
TYPE 10 INCH BONNER SPHERE COUNT, % ERROR
2305,1
TYPE 12 INCH BONNER SPHERE COUNT, % ERROR
1063,1
 0.0000000E+00,   0.0000000E+00,   0.0000000E+00,   0.0000000E+00,
 0.0000000E+00,   0.4940264     , 1000,
SAVE THESE RESULTS?
Y
LAST SPECTRUM?
N
CHANGE MATRIX, DETECTORS, UNFOLDING CODE
AND/OR ENERGY INTERVALS?
N
CHANGE THE HEADING?
N
SEARCH FOR MAXWELLIAN, 1/E INITIAL SPECTRUM?
Y
TYPE MAXWELLIAN TEMP, SHAPE, AND PERTURBATION
.5,0,.05
CHANGE FIT PARAMETERS?
Y
TYPE: END TEST(%)
      SMOOTHING FACTOR,
      CALIBRATION FACTOR,
      ITERATIONS BEFORE ERROR TEST,
      AND MAXIMUM NUMBER OF ITERATIONS
1,0,1,1,1000
CHANGE BALL DATA?
N
 0.5000000      ,   0.0000000E+00,  0.1458820      ,   0.1400000      ,
 2.985984      ,   10.29025      ,
 0.4500000      ,   0.0000000E+00,  0.1255103      ,   0.1500000      ,
 2.985984      ,   8.285000      ,
 0.4000000      ,   0.0000000E+00,  0.1118169      ,   0.1800000      ,
 4.299817      ,   5.430347      ,
 0.3500000      ,   0.0000000E+00,  0.8898502E-01  ,   0.1900000      ,
 5.159780      ,   3.348522      ,
 0.3000000      ,   0.0000000E+00,  0.6416974E-01  ,   0.2100000      ,
 6.191737      ,   1.054216      ,
 0.2500000      ,   0.0000000E+00,  0.9536391E-02  ,   0.5000000E-01,
 2.488320      ,   1.539098      ,
 0.3000000      ,   0.0000000E+00,  0,5167460      ,   0.2100000      ,
 6.191737      ,   0.7344218     , 1,
SAVE THESE RESULTS?
Y
LAST SPECTRUM?
Y

END OF EXECUTION
CPU TIME: 33.33 ELAPSED TIME:  3:54.08
EXIT
```

APPENDIX D

SAMPLE OUTPUTS OF BUNKI

(specification): b:steve2
Viewing file 'b:steve2'. Hit <space> to continue; 'Alt-V' to terminate.

TYPE BUNN.DAT
1   CF 252 IN 60 CM STEEL BALL + 1.27 CM LUCITE

RESPONSE MATRIX SAN4	UNFOLD CODE SPUN	MAXWELL TEMP,SHAPE 0.00, .00	CALIB. FACTOR 1.0000	SMOOTH FACTOR 0.0000	PER CENT ERROR 0.4940	NO. OF ITERATIONS 1000

DETECTOR	MEASURED COUNTS	CALCULATED COUNTS	PERCENT DIFFERENCE
BARE	935.000	935.163	0.017
2"+CD	2125.000	2121.371	-0.171
3"+CD	5197.000	5223.262	0.505
5·INCH	8361.000	8307.583	-0.639
8 INCH	4547.000	4579.329	0.711
10 INCH	2305.000	2289.550	-0.670
12 INCH	1063.000	1065.617	0.246

TOTAL FLUENCE=	3.426E+04	NEUTRONS/CM2
AVE ENERGY(LESS TH)=	3.104E-01	MEV
DOSE=	4.115E-05	RAD
DOSE EQUIVALENT=	3.372E-04	REM
QUALITY FACTOR=	8.194	REM/RAD
NRL TLD RESPONSE=	6.570	REM/REM(CF-252)
"HANKINS"TLD RESPONSE=	9.521	REM/REM(CF-252)
NEUTRAK RESPONSE=	0.521	REM/REM(CF-252)
NTA RESPONSE=	0.400	REM/REM(CF-252)
ANPDR-70 RESPONSE=	0.992	REM/REM(CF-252)

BIN NO.	ENERGY MAX (MEV)	FLUENCE NEUT/CM2	FLUENCE N/CM2/LETH	DOSE (RAD)	DOSE EQV. (REM)	DOSE EQV. (% OF TOTAL)
1	4.140E-07	4.409E+03	2.727E+03	2.319E-06	5.075E-06	1.505E+00
2	6.826E-07	3.949E+02	1.818E+03	2.404E-07	4.865E-07	1.443E-01
3	1.445E-06	3.489E+02	1.071E+03	2.154E-07	4.375E-07	1.298E-01
4	3.059E-06	2.968E+02	9.112E+02	1.821E-07	3.692E-07	1.095E-01
5	6.476E-06	2.814E+02	8.640E+02	1.708E-07	3.453E-07	1.024E-01
6	1.371E-05	2.778E+02	8.529E+02	1.669E-07	3.364E-07	9.978E-02
7	2.902E-05	2.939E+02	9.024E+02	1.755E-07	3.512E-07	1.042E-01
8	6.144E-05	3.167E+02	9.722E+02	1.880E-07	3.734E-07	1.107E-01
9	1.301E-04	4.070E+02	1.249E+03	2.398E-07	4.726E-07	1.402E-01
10	2.754E-04	3.889E+02	1.194E+03	2.216E-07	4.368E-07	1.295E-01
11	5.929E-04	4.741E+02	1.424E+03	2.591E-07	5.121E-07	1.519E-01
12	1.234E-03	5.177E+02	1.626E+03	2.718E-07	5.384E-07	1.597E-01
13	2.613E-03	6.231E+02	1.912E+03	3.208E-07	6.356E-07	1.885E-01
14	5.531E-03	7.779E+02	2.389E+03	3.954E-07	7.842E-07	2.326E-01
15	1.171E-02	9.992E+02	3.067E+03	5.035E-07	1.008E-06	2.990E-01
16	2.479E-02	1.324E+03	4.066E+03	7.456E-07	2.005E-06	5.947E-01
17	5.247E-02	1.870E+03	5.741E+03	1.241E-06	5.023E-06	1.490E+00
18	1.111E-01	2.903E+03	8.909E+03	2.278E-06	1.386E-05	4.111E+00
19	2.237E-01	4.483E+03	1.475E+04	4.654E-06	3.721E-05	1.104E+01
20	4.508E-01	6.445E+03	2.118E+04	9.371E-06	9.126E-05	2.707E+01
21	9.072E-01	4.617E+03	1.520E+04	1.036E-05	1.104E-04	3.274E+01
22	1.872E+00	1.422E+03	4.520E+03	4.844E-06	4.986E-05	1.479E+01
23	3.679E+00	2.886E+02	9.834E+02	1.218E-06	1.153E-05	3.419E+00
24	7.408E+00	7.049E+01	2.319E+02	4.073E-07	2.871E-06	8.513E-01
25	1.492E+01	2.413E+01	7.935E+01	1.598E-07	9.919E-07	2.942E-01

RESPONSE MATRIX	UNFOLD CODE	MAXWELL TEMP,SHAPE	CALIB. FACTOR	SMOOTH FACTOR	PER CENT ERROR	NO. OF ITERATIONS
SAN4	SPUN	0.30, .00	1.0000	0.0000	0.7344	1

DETECTOR	MEASURED COUNTS	CALCULATED COUNTS	PERCENT DIFFERENCE
BARE	935.000	931.928	-0.329
2"+CD	2125.000	2105.156	-0.934
3"+CD	5197.000	5234.559	0.723
5 INCH	8361.000	8283.147	-0.931
8 INCH	4547.000	4596.901	1.097
10 INCH	2305.000	2303.379	-0.070
12 INCH	1063.000	1067.717	0.444

TOTAL FLUENCE=	3.420E+04	NEUTRONS/CM2
AVE ENERGY(LESS TH)=	2.948E-01	MEV
DOSE=	4.106E-05	RAD
DOSE EQUIVALENT=	3.396E-04	REM
QUALITY FACTOR=	8.270	REM/RAD
NRL TLD RESPONSE=	6.597	REM/REM(CF-252)
"HANKINS"TLD RESPONSE=	8.929	REM/REM(CF-252)
NEUTRAK RESPONSE=	0.492	REM/REM(CF-252)
NTA RESPONSE=	0.399	REM/REM(CF-252)
ANPDR-70 RESPONSE=	0.999	REM/REM(CF-252)

BIN NO.	ENERGY MAX (MEV)	FLUENCE NEUT/CM2	FLUENCE N/CM2/LETH	DOSE (RAD)	DOSE EQV. (REM)	DOSE EQV. (% OF TOTAL)
1	4.140E-07	4.709E+03	2.912E+03	2.477E-06	5.420E-06	1.596E+00
2	6.826E-07	1.015E+02	4.675E+02	6.180E-08	1.251E-07	3.683E-02
3	1.445E-06	1.732E+02	5.317E+02	1.069E-07	2.172E-07	6.394E-02
4	3.059E-06	2.024E+02	6.215E+02	1.242E-07	2.518E-07	7.415E-02
5	6.476E-06	2.367E+02	7.267E+02	1.437E-07	2.904E-07	8.552E-02
6	1.371E-05	2.768E+02	8.498E+02	1.663E-07	3.352E-07	9.871E-02
7	2.902E-05	3.236E+02	9.938E+02	1.932E-07	3.868E-07	1.139E-01
8	6.144E-05	3.787E+02	1.162E+03	2.248E-07	4.464E-07	1.315E-01
9	1.301E-04	4.430E+02	1.360E+03	2.610E-07	5.144E-07	1.515E-01
10	2.754E-04	5.181E+02	1.591E+03	2.952E-07	5.819E-07	1.713E-01
11	5.929E-04	6.211E+02	1.865E+03	3.394E-07	6.708E-07	1.975E-01
12	1.234E-03	6.953E+02	2.184E+03	3.651E-07	7.232E-07	2.129E-01
13	2.613E-03	8.335E+02	2.558E+03	4.292E-07	8.501E-07	2.503E-01
14	5.531E-03	9.817E+02	3.014E+03	4.990E-07	9.895E-07	2.914E-01
15	1.171E-02	1.170E+03	3.592E+03	5.895E-07	1.180E-06	3.476E-01
16	2.479E-02	1.431E+03	4.393E+03	8.055E-07	2.167E-06	6.380E-01
17	5.247E-02	1.850E+03	5.680E+03	1.228E-06	4.970E-06	1.463E+00
18	1.111E-01	2.615E+03	8.025E+03	2.052E-06	1.249E-05	3.676E+00
19	2.237E-01	3.653E+03	1.202E+04	3.792E-06	3.032E-05	8.927E+00
20	4.508E-01	5.633E+03	1.851E+04	8.191E-06	7.977E-05	2.349E+01
21	9.072E-01	5.486E+03	1.806E+04	1.231E-05	1.312E-04	3.862E+01
22	1.872E+00	1.807E+03	5.745E+03	6.156E-06	6.337E-05	1.866E+01
23	3.679E+00	5.889E+01	2.007E+02	2.485E-07	2.352E-06	6.927E-01
24	7.408E+00	6.098E-01	2.006E+00	3.524E-09	2.483E-08	7.312E-03
25	1.492E+01	6.099E-03	2.006E-02	4.039E-11	2.507E-10	7.383E-05